Scand J Med Sci Sports 2015: ••: ••–••
doi: 10.1111/sms.12413

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

In-field gait retraining and mobile monitoring to address running biomechanics associated with tibial stress fracture

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Accepted for publication 17 December 2014

We sought to determine if an in-field gait retraining program can reduce excessive impact forces and peak hip adduction without adverse changes in knee joint work during running. Thirty healthy at-risk runners who exhibited high-impact forces were randomized to retraining [21.1 (±1.9) years, 22.1 (±10.8) km/week] or control groups [21.0 (±1.3) years, 23.2 (±8.7) km/week]. Retrainers were cued, via a wireless accelerometer, to increase preferred step rate by 7.5% during eight training sessions performed in-field. Adherence with the prescribed step rate was assessed via mobile monitoring. Three-dimensional gait analysis was performed at baseline, after retraining, and at 1-month post-retraining. Retrainers increased step rate by 8.6% ($P < 0.0001$), reducing instantaneous vertical load rate (–17.9%, $P = 0.003$), average vertical load rate (–18.9%, $P < 0.0001$), peak hip adduction (2.9° ± 4.2 reduction, $P = 0.005$), eccentric knee joint work per stance phase (–26.9%, $P < 0.0001$), and per kilometer of running (–21.1%, $P < 0.0001$). Alterations in gait were maintained at 30 days. In the absence of any feedback, controls maintained their baseline gait parameters. The majority of retrainers were adherent with the prescribed step rate during in-field runs. Thus, in-field gait retraining, cueing a modest increase in step rate, was effective at reducing impact forces, peak hip adduction and eccentric knee joint work.

Tibial stress fractures are among the most common injuries sustained by runners with a reported incidence of 4.4–15.6%, resulting in 6–12 weeks of absence from running (Callahan, 2000; Taunton et al., 2002; van Gent et al., 2007). Rehabilitation for a tibial stress fracture may last 4–17 weeks and involves a substantial amount of lost training time among military recruits (Ross & Allsopp, 2002). There is a sixfold greater risk of recurrence once an initial tibial stress fracture has been sustained, suggesting that these injuries have one of the highest recurrence rates of all running-related injuries (Tenforde et al., 2013).

Abnormal running biomechanics have been associated with tibial stress fractures. Specifically, a high loading rate of the vertical ground reaction force has been found in runners with a history of tibial stress fractures (Milner et al., 2006; Pohl et al., 2008; Zadpoor & Nikooyan, 2011). Excessive hip adduction (HADD) has also been associated with a history of tibial stress fractures (Pohl et al., 2008). It is thought that excessive HADD imparts a bending moment on the tibia, resulting in tension along the medial aspect of the bone (Pohl et al., 2008).

Gait retraining, the systematic re-education of a faulty component of gait, has been shown to reduce both impact forces (Cheung & Davis, 2011; Crowell & Davis, 2011; Clansey et al., 2014) and HADD (Noehren et al., 2010; Willy et al., 2012; Willy & Davis, 2013) during running. These previous interventions have involved treadmill running while utilizing real-time feedback on lower extremity alignment or impact forces via three-dimensional motion capture systems, a full length mirror, tibial-mounted accelerometer, or a heel sensor. Persistence in gait changes of 1–3 months have been reported, suggesting potential for longer-term changes (Noehren et al., 2010; Cheung & Davis, 2011; Crowell & Davis, 2011; Willy et al., 2012). The techniques used in the aforementioned studies require runners to cease their normal running regimens when they are enrolled in the laboratory- or clinical-based intervention. While gait changes were documented during laboratory assessments, it is unknown if runners truly adopted their retrained running mechanics to in-field running once the retraining programs were completed.

Recent technological advances have created the possibility of conducting in-field gait retraining. Wearable technologies enable real-time feedback on certain components of gait, allowing for gait retraining to be conducted outside the laboratory or clinic (Shull et al., 2014). Gait retraining interventions may now be possible in a runner's normal running environment, potentially increasing the likelihood that individuals will adopt the new running pattern. In addition, performing gait retraining in-field may reduce healthcare costs by reducing the number of clinic visits. As an added benefit, many of these devices also have the capability of mobile monitoring to determine adherence with the retrained aspect of running gait.

Conveniently, a simple increase in step rate (SR) during running may reduce several key biomechanical variables associated with tibial stress fractures, including HADD and excessive impact forces (Heiderscheit et al., 2011; Hobara et al., 2012). Interestingly, eccentric knee joint work may also be reduced with an increase in SR, suggesting that this intervention may also have applications in other running-related knee injuries such as patellofemoral pain (Heiderscheit et al., 2011; Lenhart et al., 2013; Willson et al., 2014).

There are limitations in previous work examining the effects of SR increases on various biomechanical parameters during running. As these studies were single-session designs, it is unknown if runners are able to retrain their gait to run at a higher SR to achieve lasting changes in their mechanics. Previous work examining the effect of SR increases on impact forces utilized runners with normal impact forces and therefore likely had limited potential or motivation for change. Perhaps as a result, very large (17.6–18.1%) increases in SR were determined to be necessary to reduce vertical loading rates (Hobara et al., 2012). Increases in SR of greater than 10% are metabolically costly, suggesting that these large increases in SR are unsustainable and not likely to be adopted by runners (Cavanagh & Williams, 1982). In runners with high-impact forces, a more modest increase in SR may be sufficient to significantly reduce loading rates. Finally, while the reduction in knee energy absorption per gait cycle may be potentially beneficial, additional gait cycles are necessary to cover a given unit of distance (Miller et al., 2014). Therefore, increased SR may ultimately result in greater cumulative energy absorption at the knee over a given unit of distance of running (Miller et al., 2014; Willson et al., 2014).

We sought to determine the effects of an in-field gait retraining program, using a mobile biofeedback device to cue an increase in SR, on gait parameters thought to place healthy runners at-risk for the development of tibial stress injuries. A secondary purpose was to determine adherence with the increased SR retraining cue during in-field training and monitoring sessions. We hypothesized that in-field cues to increase SR 7.5% above preferred SR would result in reductions in instantaneous and average loading rates of the vertical ground reaction forces [instantaneous vertical load rate (IVLR), average vertical load rate (AVLR)], peak HADD, eccentric knee joint work per stance phase, and eccentric knee joint work per kilometer of running. We further hypothesized that these reductions would be maintained for at least 1-month post-retraining.

Materials and methods

Based on an *a priori* power analysis of pilot data using the outcome variable with the greatest coefficient of variance, peak HADD, with an expected reduction of 3.5 degrees ($\alpha = 0.05$, $\beta = 0.20$, effect size of 0.80), it was determined that at least 26 subjects were required to adequately power this investigation. To account for a potential 10% attrition, we enrolled a total of 30 runners. All volunteers gave informed consent prior to participation. This was a dual-site study at Ohio University (20 runners) and at East Carolina University (10 runners) with ethics approval granted by the human subjects research committee of each institution. Both facilities had identical data collection equipment and all motion data were collected onsite by the primary investigator (RWW). Qualifications included running at least 11.3 km/week, 18–35 years of age, and injury free for the past 90 days. This intervention specifically targeted healthy runners who ran with elevated impact forces. In order to fully qualify, runners were required to attend a brief 15-min running impact screening in which only ground reaction forces were collected. After a 5-min self-paced warm up and treadmill accommodation period, ground reaction forces were sampled during five consecutive steps in the fifth minute of running (3.3 m/s) on an instrumented treadmill (Bertec, Worthington, Ohio, USA). Ground reaction force data were sampled at 1000 Hz and filtered with a bipole, low-pass, Butterworth filter at 50 Hz. IVLR was calculated as previously described by Milner et al. (2006) using a custom written LabVIEW program (Version 8.2, National Instruments, Houston, Texas, USA). Runners who met the IVLR qualification criterion of ≥85 body weights(bw)/second in either limb were classified as high-impact runners (HIRs) and were enrolled in the study. This qualification criterion was based on mean IVLR in a cohort of runners with a history of tibial stress fractures, corrected for a lower running speed in the present study (3.3 vs 3.7 m/s) (Milner et al., 2006). HIRs were then randomized (coin flip) by a blinded allocator to either the retraining (RT) or control (CON) groups. The limb with the highest IVLR was classified as the experimental limb for the remainder of the study.

HIRs then attended a fully instrumented, baseline data collection in which running kinematics and kinetics were collected. Three-dimensional kinematic and ground reaction force data were collected at 200 Hz and 1000 Hz, respectively, while running on an instrumented treadmill at a self-selected pace. Motion data from five consecutive strides were processed using real-time data acquisition methods (The MotionMonitor, Chicago, Illinois, USA). Ground reaction force data used to calculate IVLR and AVLR were filtered with a bipole, low-pass, Butterworth filter at 50 Hz. IVLR was calculated with the same parameters utilized in the impact screen and AVLR was also calculated as described by Milner et al. (2006). Kinematic and kinetic data were filtered at 15 Hz with a bipole, low-pass, Butterworth filter for the calculation of net joint moments via inverse dynamics (Kristianslund et al., 2012; Bezodis et al., 2013). Sagittal plane knee joint power was calculated as the product of the net knee extension moment and sagittal plane knee angular velocity. Eccentric knee joint work per stance phase was then calculated as the time integral of all negative data points of knee joint power during stance. To calculate the number of experimental limb steps needed for the subject to run 1000 m, SR was converted to step length at the self-selected running speed for each subject. Cumulative eccentric knee joint work per kilometer of running was then calculated as the eccentric knee joint work per stance phase multiplied by the number of steps by the experimental limb required to run a kilometer of distance.

Once the baseline running trial was collected, all HIRs were issued a Garmin Forerunner70 (FR70, Garmin Corporation, Olathe, Kansas, USA) wrist computer and a paired Garmin footpod that was firmly affixed to each HIRs right shoe (Fig. 1). The footpod is a triaxial accelerometer that wirelessly transmits a

Fig. 1. The Garmin FR70 that was used for all retrainers and controls: (a) A wireless accelerometer transmitted data to the wrist-mounted running computer. (b) The wrist-mounted running computer was configured such that running duration, real-time strides per minute steps per minute divided by 2 and running distance were visible to all retrainers during in-field retraining sessions 1–3, 5, and 7. (c) During infield retraining session 4, 6, and 8, retrainers were only able to view feedback on run duration and distance run as step rate feedback faded. All control subjects only viewed the display in (c).

signal (1000 Hz) to the wrist computer allowing for the real-time calculation and recording of SR and running pace. In pilot testing, the SR measurements calculated by the FR70 were found to have excellent agreement to the SR determined with an instrumented treadmill ($ICC_{3,1} = 0.98$). Treadmill and outdoor SR calculations by the FR70 also demonstrated excellent agreement ($ICC_{3,1} = 0.92$). The FR70 display was customized per group assignment such that RTs were able to see the running pace, run duration, and steps per minute whereas the CONs were only able to see running pace and run duration. Once the FR70 was issued to a runner, the device was calibrated during 400 m of self-paced treadmill running. Next, RTs were then asked to increase their SR by 7.5% over their preferred SR. Importantly, all participants were blinded to the inclusion criteria, group assignment, and the existence of the opposite group for the duration of their participation in the study.

All HIRs then returned to their normal running routine for eight training runs. During these eight runs, RTs were instructed to match their SR to the target of 7.5% above preferred SR. We utilized a self-controlled practice schedule such that RTs self-determined how often they would view the FR70 watch to receive feedback on SR. While it was expected that the amount of feedback received by each RT would vary considerably between subjects, self-controlled feedback has been suggested to result in greater engagement, enhanced motivation, and improved motor learning (Wulf et al., 2010). A faded feedback schedule (Winstein & Schmidt, 1990) was also used such that RTs were provided with real-time feedback on SR, via the FR70, during runs 1–3, 5, and 7, but did not receive feedback on runs 4, 6, and 8. This faded feedback design was utilized to encourage internalization of the new running pattern (Noehren et al., 2010; Willy et al., 2012; Willy & Davis, 2013). CONs were only asked to continue their normal running routine and were told that this study was interested in changes in their running mechanics over time.

After eight training runs, all HIRs returned for a post-retraining data collection. During this data collection, the displays of the RTs' FR70s were re-programmed such that feedback on SR was no longer visible. All HIRs then returned to their normal running routines for 30 calendar days of monitored running after which a final data collection was conducted. Running data were collected in exactly the same manner at baseline (PRE), post-retraining (POST), and 1-month post-retraining (1MO).

All mobile monitoring data were downloaded periodically from all HIR's FR70s throughout the study to assess in-field SR and running volume. Each HIR's mean SR per study phase was calculated as the total steps taken per study phase divided by the total running time per study phase. As such, mean SR for each HIR was calculated for both the retraining phase and the monitoring phase.

Data analysis was performed with SPSS Version 20 (IBM, Houston, Texas, USA). Baseline demographic data were analyzed with independent *t*-tests and Fisher's exact test to determine presence of differences between RT and CON. Running variables of interest were SR, AVLR, IVLR, peak HADD, knee power absorption, and total knee power absorption per kilometer of running. These running variables were analyzed via separate two-way, mixed model, repeated analyses of variances (ANOVAs) [group (2) × time point (3)] with an $\alpha = 0.05$. The data were assessed to determine if the assumptions of the ANOVA were met. In the case of a significant group × time interaction, post-hoc testing was conducted with an $\alpha = 0.05$ with a subsequent Holm-Bonferroni sequential correction applied (Holm, 1979). To determine the magnitude of the effect, Cohen's *d* was calculated (Cohen, 1992). In-field, mobile monitoring data from the FR70 were evaluated for adherence with the prescribed SR during the retraining phase and during the 1-month monitoring period. "Adherent" with the prescribed SR was operationally defined as an average in-field SR of at least 5% greater than baseline self-selected SR. As no change in SR was expected, CON were considered adherent if monitored SR did not differ more than 5% from their baseline SR. The 5% criterion was greater than two times the standard error of the mean of the baseline SR for the RTs, based on the ICC for the FR70 and outdoor running ("adherent" $> 2 \times (12.1 \times \text{square root}(1–0.92))$). As such, any value exceeding the 5% criterion would partly represent a conscious effort to alter one's SR. A Fisher's exact test comparing the RTs and CONs was performed to determine adherence based on the adherence criterion for each study phase. Please see Fig. 2 for the CONSORT study diagram.

Results

A total of 83 volunteers were screened to obtain the 30 runners who qualified as HIRs (Table 1). There were no significant differences between groups. One CON subject was lost because of injury soon after the retraining phase began. Therefore, an intention-to-treat analysis of last observation carried forward was performed. There were significant group × time interactions for SR ($P < 0.0001$), IVLR ($P = 0.034$), AVLR ($P = 0.007$), peak HADD ($P = 0.005$), eccentric knee joint work

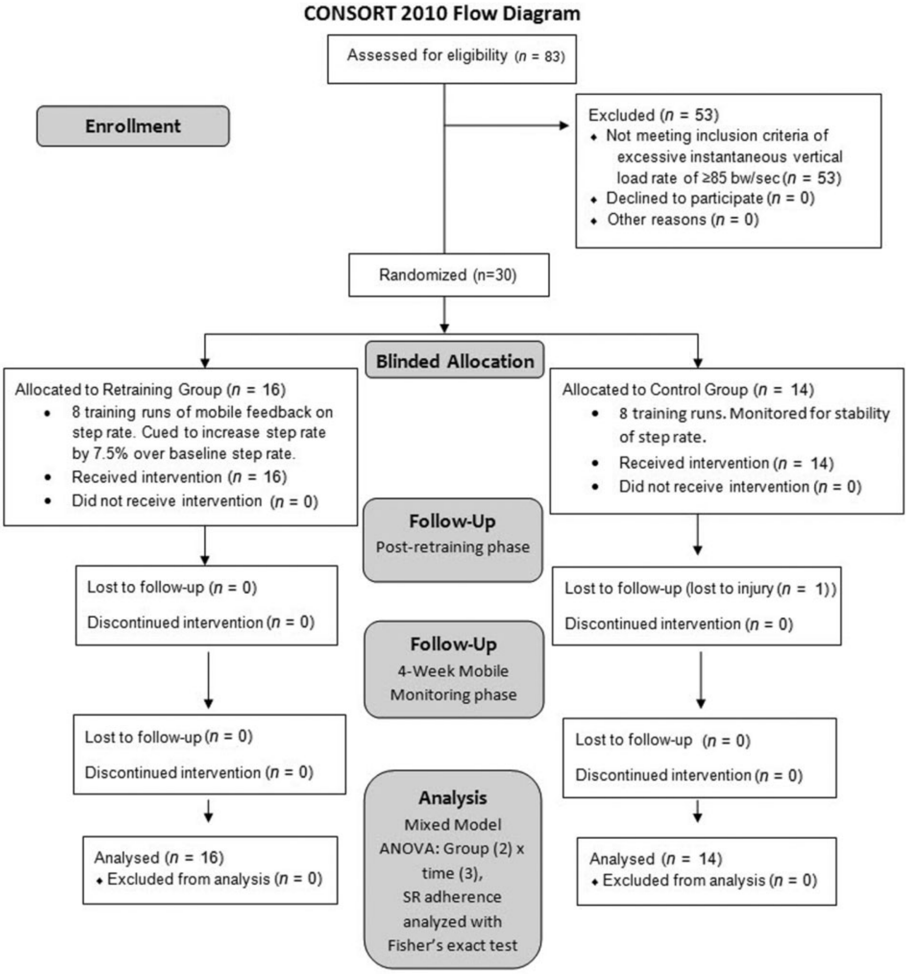

Fig. 2. CONSORT 2010 diagram.

Table 1. Demographics for subjects

Variable	Retrainers	Control	*P* value
Age (months)	251.9 (16.3)	248.8 (15.0)	0.99
Body mass index (kg/m^2)	23.0 (2.6)	23.4 (3.3)	0.73
Reported running volume prior to study (km/week)	22.1 (10.8)	23.2 (17.9)	0.83
Self-selected running pace (m/sec)	3.21 (0.27)	3.16 (0.28)	0.60
Males/females (*n*)	7/9	9/5	0.30

($P < 0.0001$), and eccentric knee joint work per kilometer ($P = 0.002$) (Table 2). From PRE-POST for the RTs, subsequent pairwise comparisons revealed significant increases in SR ($P < 0.0001$, $d = 1.33$), while reductions in IVLR ($P = 0.003$, $d = -1.18$), AVLR ($P < 0.0001$, $d = -1.32$) (Fig. 3), peak HADD $P = 0.005$, $d = -0.74$), eccentric knee joint work ($P < 0.0001$, $d = 1.00$), and eccentric knee joint work per kilometer ($P < 0.0001$, $d = -0.90$) occurred. Similarly, at 1MO for the RTs, a significant increase in SR ($P < 0.0001$, $d = 1.21$) and reductions in IVLR ($P = 0.001$, $d = -1.21$), AVLR ($P = 0.0001$, $d = -1.44$), peak HADD ($P = 0.003$, $d = -0.61$), eccentric knee joint work ($P < 0.0001$, $d = -0.81$), and eccentric knee joint work per kilometer ($P = 0.004$, $d = -0.60$) occurred compared with baseline. For CON, no significant changes occurred at either the POST or 1MO time points compared with baseline levels. For SR, IVLR, and AVLR, there were significant group differences between RT and CON at POST (SR $P = 0.001$, IVLR $P = 0.005$, AVLR $P = 0.003$) and 1MO (SR $P = 0.007$, IVLR $P = 0.012$, AVLR $P = 0.026$). However, there were no differences between groups for peak HADD, knee power absorption, and knee power absorption per kilometer at POST and 1MO.

During the retraining period and during the 30-day monitoring period, mean in-field SR was 178.4 steps per minute (SR; (±9.6) and 177.0 SR (±9.0), respectively (Table 3). During the retraining phase, 12 of the 16 RTs met the operational definition of adherence with the prescribed SR. In the 30-day post-retraining monitoring period, 10 of the 16 RTs met the operational definition of

Table 2. Results for the analysis of variance [group(2) × time (3)] at each time point for the laboratory assessment of running biomechanics

Variable	Group	Baseline	Post	1MO	*P* value
Steps per minute (SPM)	RT	166.5 (160.1–172.9)	180.8*† (174.9–186.6)	180.6*† (174.1–187.1)	Group × time
	CON	166.7 (160.7–172.7)	169.7 (163.4–176.0)	168.6 (162.7–174.5)	< 0.0001
Instantaneous vertical load rate (bw/s)	RT	101.3 (96.0–106.5)	83.2*† (72.0–94.3)	83.5*† (73.1–93.9)	Group × time
	CON	108.0 (99.6–116.3)	104.5 (94.8–114.2)	102.6 (91.5–113.7)	0.034
Average vertical load rate (bw/s)	RT	75.6 (71.4–79.7)	61.3*† (53.9–68.6)	60.4* (53.4–67.5)	Group × time
	CON	77.2 (68.0–86.3)	79.2 (69.9–88.4)	74.8 (63.3–86.3)	0.007
Peak hip adduction (degrees)	RT	14.7 (12.6–16.8)	11.8* (9.7–13.9)	12.2* (9.9–14.5)	Group × time
	CON	11.8 (8.6–15.0)	13.0 (10.1–15.8)	12.7 (10.7–14.7)	0.005
Eccentric knee work per stance (J/kg*m)	RT	–0.33 (–0.39––0.28)	–0.24* (–0.28––0.2)	–0.26* (–0.3––0.22)	Group × time
	CON	–0.30 (–0.35––0.24)	–0.29 (–0.34––0.25)	–0.31 (–0.38––0.26)	< 0.0001
Eccentric knee work per km (J/kg*m)	RT	–144.8 (–166.7––123.0)	114.2* (–128.7––99.7)	–123.3* (–140.3––106.4)	Group × time
	CON	–129.8 (–149.2––110.3)	–130.9 (–149.6––112.3)	–140.9 (–161.8–120.0)	0.002

Data represent group mean and 95% confidence intervals. Post refers to the data collection that occurred immediately following the post-retraining phase. 1MO refers to the data collection that occurred at the conclusion of the 1-month monitoring period.

*Significantly different than baseline ($P < 0.05$ with Holm-Bonferroni sequential correction applied).

†Significantly different than control for same time point ($P < 0.05$).

CON, control; RT, retrainers.

Table 3. Mobile monitoring data uploaded from the running computer for the RT and CON groups. Number adherent represents the number of RTs who ran at least 5% over baseline preferred step rate and CONs who ran within 5% of baseline step rate, respectively

Training phase		Steps per minute	Number adherent (x/16)	Fisher's exact test
Prescribed steps per minute	RT	179.0 (13.0)	n/a	n/a
	CON	166.7 (10.3)	n/a	
Retraining monitoring during in-field sessions	RT	178.0 (9.2)	12/16	*P* = 0.34
	CON	167.4 (8.3)	13/14	
One-month monitoring during in-field sessions	RT	176.8 (9.0)	10/16	*P* = 0.09
	CON	168.0 (7.8)	13/14	

CON, control; n/a, not applicable; RT, retrainers.

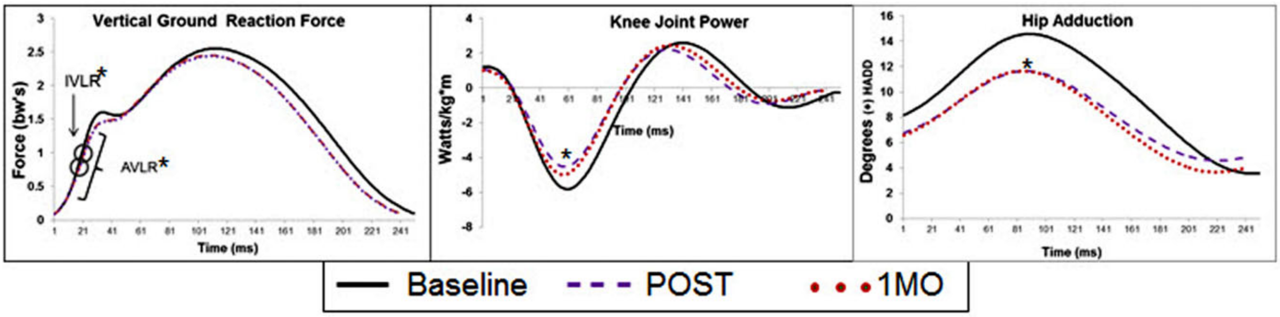

Fig. 3. Group mean vertical ground reaction force, knee joint work, and hip adduction curves for the three laboratory gait sessions for the retrainers. Average vertical load rate was calculated as the derivative of the middle 60% of the vertical ground reaction force curve to the vertical impact peak. Instantaneous vertical load rate was measured as the greatest derivative between two adjacent data points along the same interval. Eccentric knee joint work (J/kg*m) was calculated as the time integral for all negative knee joint power in the first 75% of stance. To illustrate the change in stance length, ensemble curves were normalized to mean stance length per study phase.
*Significantly different than baseline ($P < 0.05$ with Holm-Bonferroni sequential correction applied).
‡Significantly different than Control for same time point ($P < 0.05$).

adherence with the prescribed SR. During both the retraining and 30-day monitoring phases, 13 of the 14 CONs were "adherent" i.e. monitored SR remained within 5% of the baseline measures, yielding no differences with the RTs during each training phase.

Discussion

We sought to determine if a mobile biofeedback, in-field gait retraining program was effective at reducing several key biomechanics factors that have been associated with tibial stress fractures. A modest cue of a 7.5% increase in preferred SR resulted in reductions in IVLR, AVLR, peak HADD, and peak knee joint power absorption. The increase in SR and reductions in IVLR, AVLR, peak HADD, and peak knee joint power absorption were maintained at the 1MO follow-up. Mobile monitoring data revealed that 12 of the 16 of the RTs met the SR prescription. Further, mobile monitoring indicated that the majority of the RTs incorporated the new running pattern during routine runs through at least 1MO. Our findings suggest that persistent effects of in-field gait retraining of uninjured runners are feasible and need not be isolated to laboratory or clinical settings.

In HIRs, we found that cueing a modest increase in SR of 7.5% above the preferred SR was adequate to reduce IVLR and AVLR. These reductions were associated with large effect sizes and 18.9% and 17.9% reductions, respectively. Thus, large SR increases in excess of 10% over the preferred SR are not necessary to reduce impact forces in HIRs, as has previously been suggested in runners with normal impacts (Hobara et al., 2012). This finding highlights the need to target interventions for specific faults in running mechanics. As SR increased, a reduction in vertical velocity and excursion of the center of mass was the likely mechanism for a reduction in impact forces (Derrick et al., 1998). Edwards et al. suggested that a 10% reduction in stride length (corresponding to a 10% increase in SR) reduced tibial contact forces and a subsequent reduced risk of probabilistic stress fracture in runners (Edwards et al., 2009). In contrast, a 10% increase in stride length was found to increase risk of stress fracture (Edwards et al., 2009). The findings in the present study, coupled with the probabilistic model findings, suggest that the HIRs experienced reduced tibial forces and a potential reduction in tibial stress fracture risk. The decrease in peak HADD may have also reduced bending forces on the tibia, further suggesting potential of this intervention to reduce tibial stress fracture risk (Pohl et al., 2008). However, modeling of tibial forces with this cohort is necessary to confirm this reasoning. Prolonged follow-up (> 1 year) and a larger sample size is needed to determine if running with an increased SR reduces tibial stress fracture incidence in an at-risk population.

Despite performing all retraining sessions independently and in-field, reductions in the present study compare favorably with the laboratory-based tibial shock retraining studies of Clansey et al. (2014) (ALVR = −17.8%, IVLR = −19.1%) and Crowell and Davis (2011) (ALVR = −32%, $d = -1.5$, IVLR = −34%, $d = -1.7$). At 1MO, RTs continued to run with 20.0% ($d = -1.44$) and 17.5% ($d = -1.21$) lower AVLRs and IVLRs than at PRE, respectively. The persistence of change suggests that there is potential for longer-term reductions in impact forces with this retraining technique. It is possible that explicitly changing SR is an easier task than reducing the abstract measure of tibial shock. Interestingly, Clansey et al. (2014) did not find any retention in the reduction of AVLR or IVLR at 30 days post-tibial shock retraining. The difference in outcome may be due to differences in the feedback schedules used in the respective studies. While this study design utilized a faded feedback and self-controlled schedule, Clansey et al. (2014) provided constant feedback on tibial shock. Indeed, constant feedback may be detrimental to skill acquisition (Winstein & Schmidt, 1990; Wulf et al., 2002). Interestingly, Crowell and Davis (2011) utilized a faded feedback schedule similar to the one used in the present study and found similar rates of retention at 30 days (ALVR = −32%, $d = -1.3$; IVLR = −34%, $d = -1.7$) as the present study. The conflicting results between the present study, Crowell and Davis (2011) and Clansey et al. (2014) at post-retraining follow-ups suggest the need for a greater study of various feedback schedules in gait retraining interventions.

The approximately 3-degree reduction in peak HADD was of similar magnitude to the reductions reported in a prior SR modification investigation in healthy individuals (Heiderscheit et al., 2011). Further, this reduction exceeds the reported ~1.5 degree within tester measurement error associated with repeated measures of peak HADD (Ferber et al., 2002). While excessive impact forces have been suggested to play a role in patellofemoral pain (Thijs et al., 2007; Cheung & Davis, 2011), evidence supporting faulty proximal mechanics is more convincing (Huberti & Hayes, 1984; Willson & Davis, 2008; Salsich & Long-Rossi, 2010; Noehren et al., 2013). A reduction in peak HADD has been suggested to result in a reduction in the dynamic quadriceps angle, leading to a reduction in lateral tracking of the patella (Huberti & Hayes, 1984; Powers, 2010). Therefore, cueing an increase in SR may be a beneficial gait modification in individuals with patellofemoral pain. Previously, an approximate 6-degree reduction in peak HADD was reported in gait retraining interventions that specifically cued a reduction in HADD in females with patellofemoral pain (PFP) and who had excessive HADD (Noehren et al., 2010; Willy et al., 2012). Besides not directly cueing a reduction in peak HADD, the lack of a female-only, symptomatic population with elevated peak HADD may be at least partially responsible for the lower reduction of this variable in the present investigation. Although widely practiced, posterolateral hip strengthening appears to have no effect in reducing HADD in female runners (Snyder et al., 2009; Willy & Davis, 2011; Wouters et al., 2012). As such, gait retraining may be preferred over posterolateral hip strengthening when a reduction in HADD is desired. Despite the significant reductions in peak HADD, there were no differences between groups at POST and 1MO. Despite the lack of difference between groups, moderate effect sizes were present for the RTs at baseline-POST ($d = -0.74$) and baseline-1MO ($d = -0.61$), suggesting a clinically meaningful effect.

Even when considering the extra stance phases to run a kilometer, cumulative load on the knee extensor mechanism was reduced at POST and 1MO. The reduction in cumulative load is an important consideration as the RTs were estimated to require 38.2 ± 18.3 and 37.1 ± 17.5 more steps to run 1 km at POST and 1MO, respectively. This reduction in eccentric knee joint work at the knee may be especially beneficial in runners who are recovering from injuries to the quadriceps mechanism such as patellofemoral pain, patellar tendinopathy, and Osgood-Schlatter's syndrome. (Willson et al., 2014). In addition, a reduction in cumulative tibiofemoral contact forces may also be a result. Due to the lower cumulative load of the extensor mechanism, this intervention may be beneficial in runners with patellofemoral and tibiofemoral joint osteoarthritis.

While all RTs increased their SR during the retraining sessions, 12 of the 16 actually met or exceeded the operational definition of adherence with the prescribed SR of 7.5% greater than preferred. This level of adherence is impressive considering elevation changes, running pace, or running surfaces were not controlled during any of the in-field retraining sessions. Interestingly, three of the four RTs who were considered to be non-adherent also had the lowest increases in SR at POST during in the laboratory gait assessments (mean increase (SD) in SR for non-adherent RTs at POST = +4.4% (1.6). Thus, it is possible that the non-adherent RTs simply had difficulty changing their SR because of lower extremity anthropometrics or baseline running mechanics. The RT with the highest baseline SR (194 SPM) is a compelling example. This female participant only increased her SR by 2.5% over the preferred SR at both time points and reported hip discomfort during the retraining sessions. These laboratory SR values were confirmed with her mobile monitoring data from the FR70 that indicated that this runner failed to achieve greater than a 3% increase in SR during any in-field runs. Thus, there may be a ceiling effect on the ability to increase SR in runners with a high baseline SR. Interestingly, this individual actually ran with AVLR and IVLR values at POST that were greater than baseline, suggesting that an increase in SR may not be appropriate for all runners with high-impact forces. In contrast, the RT with the lowest baseline SR (138 SPM) reported ease in meeting the SR prescription during in-field retraining sessions. At the post-retraining data collection, this subject had correspondingly large reductions of 35.7% and 43.2% in AVLR and IVLR, respectively.

In the absence of feedback during the 30-day monitoring period, 10 of the 16 RTs continued to meet the definition of adherence with the prescribed SR during in-field runs. All runners ran with a monitored SR that was greater than baseline SR (+6.0% ± 4.1), but the increases ranged from 1% to 17% over baseline SR. Based on this finding, it is possible that some RTs may have benefited from periodic retraining sessions to maintain the increased SR during in-field running. Whether long-term adherence differs in a pathological population of runners, such as those with medial tibial stress syndrome or patellofemoral pain, is presently unknown.

Limitations and future directions

This study had several limitations that should be kept in mind when interpreting these findings. First, the study was conducted in healthy runners who demonstrated a characteristic previously associated with the occurrence of tibial stress fractures. Therefore, these findings should not be considered to be applicable to injured runners and those with normal levels of impact forces. Further study should be conducted in symptomatic populations, such as runners with medial tibial stress syndrome or an overuse knee injury, or those with a history of tibial stress fractures. While not the aim of this study, the short follow-up period of 30 calendar days, coupled with relatively low subject numbers, precluded the ability to assess changes in stress fracture incidence and long-term persistence of the retrained SR. A further limitation was that there were no between group differences at POST and 1MO in the secondary variables of peak HADD, eccentric joint power, and eccentric joint power per kilometer. The lack of significant differences between groups suggests that the current investigation may have been underpowered for these variables to demonstrate between group differences.

In conclusion, the results of this study suggest that gait retraining using SR feedback can be conducted in-field without interruption of one's normal running routine. Further, this study demonstrated that SR retraining reduced several key biomechanical variables that are associated with tibial stress fractures. This protocol may have application in the treatment of other overuse running injuries, such as patellofemoral pain. In-field gait retraining may be especially useful in certain populations who are unable to cease normal run training, such as military or elite populations.

Perspective

Laboratory- and clinic-based gait retraining programs are effective at reducing several biomechanical variables associated with tibial stress fractures. However, these programs require supervised clinic visits and adherence with the new gait patterns are unknown. Wearable technologies offer the potential to perform gait retraining in-field and to monitor adherence with a retrained gait pattern. As in previous acute studies of increasing SR, this in-field gait retraining investigation yielded reductions in impact forces, eccentric knee joint work, and hip adduction. Promisingly, these gait alterations were maintained for at least 30 days post-retraining suggesting potential for long-term changes. While further investigation is necessary to determine if in-field gait retraining reduces the incidence or recurrence of tibial stress

fractures, these findings suggest that instrumented gait retraining does not need to be restricted to laboratory or clinical settings.

Key words: Running, gait retraining, tibial stress fractures, knee, biomechanics, hip.

Acknowledgements

Funding was provided by the Ohio University Summer Research Award. Scott Hadding, Wesley Brown and Nathan Blaylock assisted with data collections and analysis.

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